Electron Beam Induced Damage

An Atom-by-atom Investigation with TEAM0.5

A next generation electron microscopes is currently being developed by the Department of Energy as a collaborative effort to redesign the instruments around aberration corrected optics [1]. Within this project, the TEAM 0.5 prototype microscope is currently being commissioned. The instrument is equipped with a high brightness gun and a monochromator [2]. However, already in the past concerns were raised [3] and debated [4] that the high current density in field emission microscopes may alter the atomic structure of materials too fast to record undamaged images of compound semiconductors. Concerns about electron beam induced knock-on damage are indeed very relevant because the TEAM project aims at reconstructing the three dimensional structure of materials at atomic resolution, which requires maintaining structural integrity. On the other hand detailed knowledge about knock-on and ionisation damage in such microscopes is absent and the TEAM0.5 microscope is ideally suited for such investigations since its unprecedented performance allows for the detection of single atoms of most elements of the periodic system [2].

This contribution addresses electron beam induced damage at the single atom level in a variety of materials including InGaN alloys, In_2O_3, CdS, Ge and graphene. Two examples are shown in figures 1 and 2. Figure 1 documents that heavy (In) and light (O) atoms can be detected side by side in one phase image with intensity differences that allow for element identification. It is seen that the crystal is oxygen terminated towards the vacuum. Moreover, we confirm previous investigations of beam induced atom and atom column displacements at the gold vacuum interface [5] since indium atom displacements at the crystals surface is detected, too, but such events occur less frequently at In_2O_3 surfaces than at gold surfaces. In case of graphene (fig. 2), we find from time resolved measurements that electron beam damage scales with the strength the atoms are bound to their neighbours: surface or edges atoms are affected most and the electron beam commonly stimulates surface diffusion. However, even if extreme illumination conditions are employed as reported in figures 1 and 2 we find that beam induced damage is controllable at the single atom level and that even the amorphous structure of weakly bound adsorbents can be maintained and resolved in single images if 80kV of acceleration voltage is utilised.

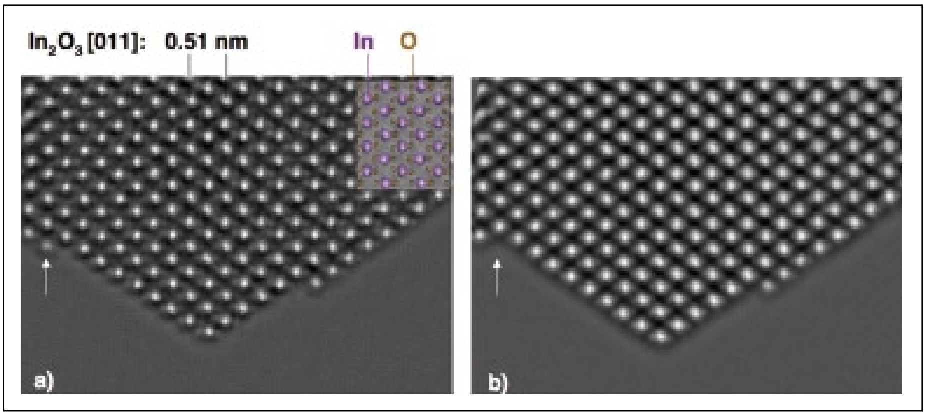

Fig. 1: Reconstructed phase images of In_2O_3 [011] from a focal series of 26 lattice images. a) Phase from images 1–13 with model inserted b) Phase from images 14-26. The crystal is oxygen terminated. The arrow marks an atom column that disappears after recording image 13. Reconstruction aperture: 0.5 Å; 300 kV; recording interval between images: 3 sec; current density: $3\ 10_4$ e/$Å_2$s; monochromator switched on.

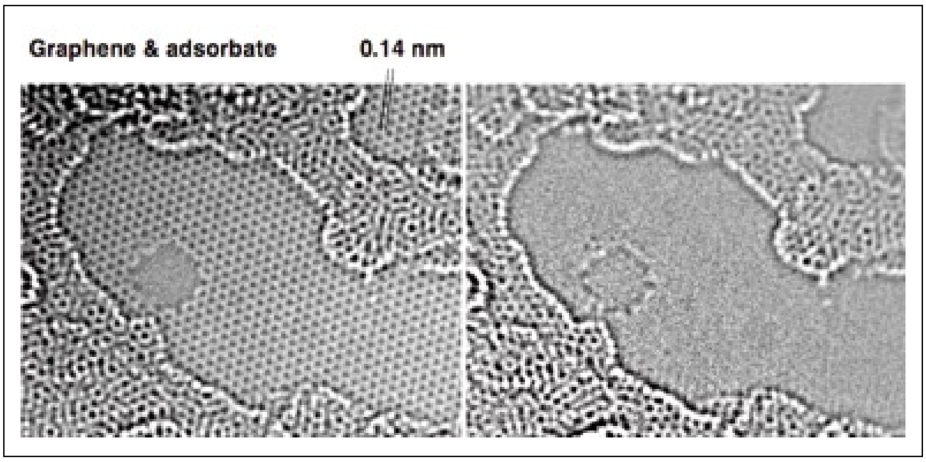

Fig. 2: a) Lattice image of graphene with monolayer adsorbates. Carbon atoms are imaged bright. b) The lattice fringes of the monolayer graphene sheet are removed from the image. The amorphous structure of the adsorbate is resolved in single images. 80 kV; current density: $1.4\ 10^5$ e/$Å^2$s; monochromator switched on.

Keywords:

InGaN, In_2O_3, CdS, Ge, C, Aberration-corrected electron microscopy, single atom detection, radiation damage

Crystalline structures can be maintained across many lattice images without introducing damage. As a result it is possible to reconstruct the electron exit wave function of graphene membranes to obtain images of single carbon atoms with a signal-to-noise ratio of 8–10 as shown in figure 3. To our knowledge such signal-to-noise ratio was not achievable before and it becomes obvious that TEAM 0.5 can detect single atoms of all elements from the Periodic Table unless they escape detection by radiation damage. [6]

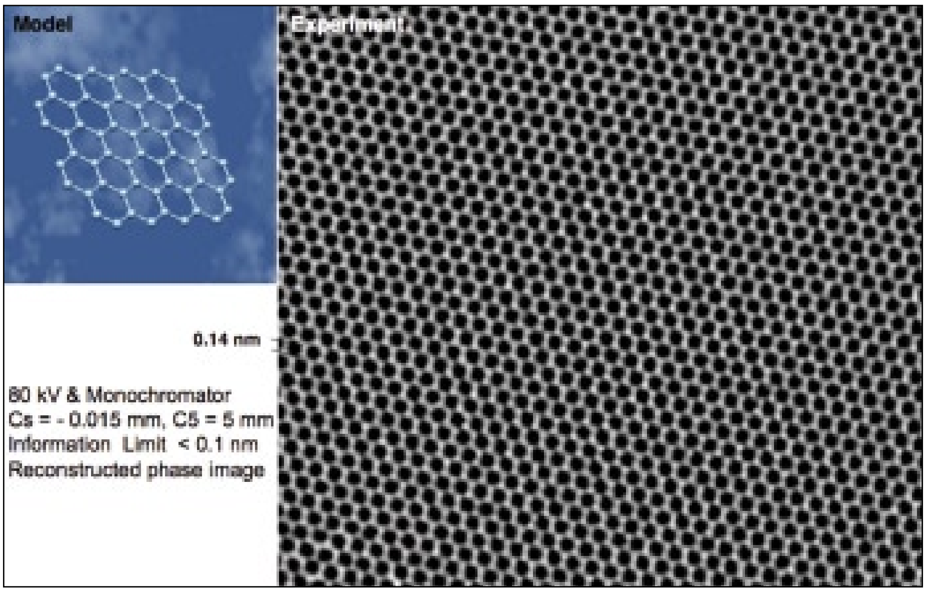

Fig. 3: Reconstructed phase image of graphene from a focal series of 15 lattice images. Single carbon atoms are imaged with signal/noise = 8–10

References

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Contact:
Christian Kisielowski
R. Erni
National Center for Electron Microscopy
Lawrence Berkeley National Laboratory
Berkeley, USA
cfkisielowski@lbl.gov

J. Meyer
Department of Physics
University of California at Berkeley, USA